HIGASHINO, U.S. Patent Application Serial No. 09/855,371, Filed: May 15, 2001

MICRO PUMP

[0001] This application is based on Patent Application No. JP2000-143124 filed in Japan, the content of which is hereby incorporated by reference.

BACKGROUND OF THE INVENTION

FIELD OF THE INVENTION

[0002] The present invention relates to an improved micro pump, and specifically relates to a micro pump for transporting minute amounts of fluid with high accuracy.

DESCRIPTION OF THE RELATED ART

[0003] The principal methods used by micro pumps to transport minute amounts of fluids include a first mechanical method using a check valve, and a second method using, in place of the check valve, a nozzle having a different flow pass resistance in the fluid flow direction. A micro pump using the first method is disclosed in Japanese Laid-Open Patent Application No. HEI 11-257233, wherein a fluid is pressurized within the pump by operating a diaphragm, and this pressure is used to operate a check valve to transport the fluid. Japanese Laid-Open Patent Application No. HEI 10-299659

discloses a micro pump provided with a movable valve in a nozzle unit communicating with a pressure chamber, wherein a piezoelectric element is used to open and close the movable valve to provided directionality to the flow of the fluid.

[0004] Japanese Laid-Open Patent Application No. HEI 10-110681 discloses a micro pump using the second method provided with a projecting member in a nozzle unit communicating with a pressure chamber so as to have different flow pass resistance depending on the direction of the flow. This micro pump makes it difficult for fluid to start flowing in the opposite direction to a desired flow direction, such that the fluid is transported in one desired direction.

[0005] Since micro pumps using the first method are provided with a check valve or movable valve, such micro pumps are mechanically complex, and readily susceptible to mechanical deterioration. Furthermore, the micro pump disclosed in Japanese Laid-Open Patent Application No. HEI 10-299659 requires at least three piezoelectric elements including a piezoelectric element to operate the movable pump, and a piezoelectric element to change the pressure of the pressure chamber. A further disadvantage arises in that these piezoelectric elements are operated individually, the drive circuits are complex.

[0006] Micro pumps using the second method cannot transport a fluid in only a single direction.

OBJECTS AND SUMMARY

[0007] An object of the present invention is to provide an improved micro pump to eliminate the previously described disadvantages. More specifically, the present invention provides a micro pump capable of transporting minute amounts of fluid in both forward and reverse directions with high accuracy using a simple construction.

[0008] These and other objects are attained by one aspect of the present invention providing a micro pump comprising a first flow pass which changes flow pass resistance in accordance with a differential pressure, a second flow pass wherein the percentage change in the flow pass resistance corresponding to a differential pressure is smaller than that of the first flow pass, a pressure chamber connected to the first flow pass and the second flow pass, and an actuator for changing the pressure force within the pressure chamber. The differential pressure referred to herein is the pressure force at bilateral ends of a flow pass.

[0009] According to this aspect, the first flow pass has a resistance which changes in accordance with a

differential pressure, and the percentage change in the resistance of the second flow pass corresponding to the differential pressure is smaller than that of the first flow pass. Accordingly, the ratio of the resistance of the first flow pass and the resistance of the second flow pass is different when the differential pressure is large and when the differential pressure is small. Since the actuator changes the pressure force within the pressure chamber connected to the first flow pass and the second flow pass, the ratio of the flow pass resistance of the first flow pass and the resistance of the second flow pass can differ by changing the pressure within the pressure chamber. Therefore, a micro pump is provided which is capable of transporting minute amounts of fluid in forward and reverse directions with high accuracy using a simple construction.

[0010] It is desirable that the first flow pass and the second flow pass of the micro pump respectively have uniform cross sectional configurations taken in a plane that is orthogonal to the flow direction, and that the percentage of the cross sectional area relative to the flow pass length of the first flow pass is greater than the percentage of the cross sectional area relative to the flow pass length of the second flow pass.

[0011] According to this aspect, the ratio of the flow pass resistance of the first flow pass and the resistance of the second flow pass can differ when the differential pressure is large and when the differential pressure is small, since the first flow pass and the second flow pass respectively have uniform cross sectional configurations taken in a plane that is orthogonal to the flow direction such that the percentage of the cross sectional area relative to the flow pass length of the first flow pass is greater than the percentage of the cross sectional area relative to the flow pass length of the second flow pass.

[0012] It is further desirable that the first flow pass of the micro pump has any shape among a shape which rapidly changes cross sectional configurations taken in a plane that is orthogonal to the flow direction, a shape in which the center line is not straight, or a shape having an obstruction in the flow pass.

[0013] According to this aspect, the percentage change in the flow pass resistance relative to the change in differential pressure of the first flow pass is greater than that of the second flow pass since the first flow has any shape among a shape which rapidly changes cross sectional configurations taken in a plane that is orthogonal to the flow direction, a shape in which the

center line is not straight, or a shape having an obstruction in the flow pass.

[0014] It is desirable that the micro pump is provided with drive means for driving the actuator to repeatedly change the volume of the pressure chamber between first volume and second volume at specific intervals, and this repetition is such that the time when increasing the volume of the pressure chamber and the time when decreasing the volume of the pressure chamber are different.

[0015] According to this aspect, the drive means drives the actuator to repeatedly change the volume of the pressure chamber between the volume of the first flow pass and the volume of the second flow pass at specific intervals. Since the time of increasing the volume of the pressure chamber and the time of decreasing the volume of the pressure chamber differ in this repetition, the differential pressures of the first flow pass and the second flow pass are different when the volume is increasing and when the volume is decreasing. As a result, the structure of the actuator may be simplified.

[0016] It is desirable that the driving means of the micro pump is capable of a first repetition and a second repetition wherein the times for increasing the volume of the pressure chamber differ.

[0017] According to this aspect, the direction of transport of the fluid in the first repetition is different from that of the second repetition because the time for increasing the volume of the pressure chamber is different in the first repetition and the second repetition.

[0018] It is desirable that the micro pump is provided with a drive means for driving an actuator to repeatedly change the volume of a pressure chamber between first volume and second volume at specific intervals, and the first flow pass has a flow pass resistance in a first direction which is greater than the flow pass resistance in a second direction opposite to the first direction, such that the drive means is capable of driving in a first repetition wherein the time of increasing the volume is identical to the time of decreasing the volume, and a second repetition wherein the time of increasing the volume is different from the time of decreasing the volume.

[0019] According to this aspect, the drive means drives the actuator to repeatedly change the volume of the pressure chamber between the volume of the first flow pass and the volume of the second flow pass at specific intervals. Since the first flow pass has a flow pass resistance in a first direction which is greater than the

flow pass resistance in a second direction opposite to the first direction, a fluid is transported in a second direction in the first repetition wherein the time of increasing the volume is identical to the time of decreasing the volume, and a fluid is transported in a first direction in the second repetition wherein the time of increasing the volume differs from the time of decreasing the volume. Therefore, fluid can be effectively transported in both a forward direction and an opposite direction.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020] These and other objects and features of the present invention will become apparent from the following description of the preferred embodiments thereof taken in conjunction with the accompanying drawings, in which:

[0021] FIG. 1 is a partial section view of a micro pump of an embodiment of the present invention;

[0022] FIG. 2 is a partial plan view of the micro pump of the embodiment of the present invention;

[0023] FIG. 3 shows the relationship between differential pressure and the flow pass resistance of the first flow pass and the second flow pass of the micro pump of the present embodiment;

[0024] FIG. 4 shows the deportment of a fluid and a first voltage waveform applied to a piezoelectric element;

[0025] FIG. 5 shows the deportment of a fluid and a second voltage waveform applied to a piezoelectric element;

[0026] FIG. 6 shows a modification of the waveform of a voltage applied to a piezoelectric element by a drive unit 120 of the micro pump of the present embodiment;

[0027] FIG. 7 shows a first example of the shape of the first flow pass of the micro pump of the present embodiment;

[0028] FIG. 8 shows a second example of the shape of the first flow pass of the micro pump of the present embodiment;

[0029] FIG. 9 shows a third example of the shape of the first flow pass of the micro pump of the present embodiment;

[0030] FIG. 10 shows a fourth example of the shape of the first flow pass of the micro pump of the present embodiment;

[0031] FIG. 11 shows a fifth example of the shape of the first flow pass of the micro pump of the present embodiment;

[0032] FIG. 12 shows a sixth example of the shape of the first flow pass of the micro pump of the present embodiment;

[0033] FIG. 13 shows a seventh example of the shape of the first flow pass of the micro pump of the present embodiment;

[0034] FIG. 14 is a plan view of a first modification of the micro pump of the present embodiment

[0035] FIG. 15 shows an example of the voltage applied to the piezoelectric element by the drive unit in the first modification of the micro pump of the present embodiment;

[0036] FIG. 16 shows another example of the waveform of the voltage applied to the piezoelectric element by the drive unit in the first modification of the micro pump of the present embodiment;

[0037] FIG. 17 is a plan view of a second modification of the micro pump of the present embodiment; and

[0038] FIG. 18 shows the relationship between the differential pressure and the flow pass resistance of the first flow pass and the second flow pass of the second modification of the micro pump of the present embodiment.

[0039] In the following description, like parts are designated by like reference numbers throughout the several drawings.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0040] The preferred embodiments of the present invention are described hereinafter with reference to the accompanying drawings. In the drawings, like reference numbers refer to like or equivalent parts, and descriptions thereof are not repeated.

[0041] FIG. 1 is a partial section view of the micro pump of an embodiment of the present invention. FIG. 2 is a partial plan view of a micro pump of an embodiment of the present invention. Referring to FIGS. 1 and 2, a micro pump 100 includes a base plate 101 which forms a first fluid chamber 111, first flow pass 115, pressure chamber 109, second flow pass 117, and second fluid chamber 113, and a top plate 103 superimposed on the base plate 101, an oscillating plate 105 superimposed on the top plate 103, a piezoelectric element 107 superimposed on the side opposite the pressure chamber 109 on the surface of the oscillating plate 105, and a drive unit 120 for driving the piezoelectric element 107.

[0042] The base plate 101 is a photosensitive glass base plate having a thickness of 500 μm, on which is formed the first fluid chamber 111, first flow pass 115, pressure chamber 109, second flow pass 117, and second fluid chamber 113 by etching to a depth of 100 μm. In

the present embodiment, the first flow pass 115 has a width of 25 μm, and length of 20 μm. The second flow pass 117 has a width of 25 μm, and a length of 150 μm. Accordingly, the first flow pass 115 and the second flow pass 117 have identical widths and depths, but the length of the second flow pass 117 is longer than the length of the first flow pass 115.

[0043] The first flow pass 115 and the second flow pass 117 are not limited to being formed in a slit-like shape by etching the base plate 101, and also may be formed by drilling, punch-pressing, and boring via laser process or the like of the plate.

[0044] The top plate 103 is a glass plate, and is superimposed on the base plate 101 to form the top surface of the first fluid chamber 111, first flow pass 115, second fluid chamber 113, and second flow pass 117. The part at the top surface of the pressure chamber 109 of the top plate 103 is a pass-through formed by etching or the like.

[0045] The oscillation plate 105 is a thin glass plate having a thickness of 50 μm. The piezoelectric element 107 is a piezoelectric ceramic; in the present embodiment, a lead zirconate-titanate (PZT) ceramic 50 μm in thickness is used in the present embodiment. The

piezoelectric element 107 and oscillation plate 105 are adhered using an adhesive or the like.

[0046] The drive unit 120 generates a voltage of a specific waveform to apply a drive voltage to the piezoelectric element 107. The oscillation plate 105 and the piezoelectric element 107 are subject to unimorph mode flexing deformation (warping deformation by applying the drive voltage from the drive unit 120 to the piezoelectric element 107. In this way the volume of the pressure chamber 109 is increased or decreased.

[0047] In the micro pump 100 of the present embodiment, when a voltage of 30 V is applied to the piezoelectric element 107, the deformation of the piezoelectric element 107 attains a displacement of 80 nm, and generates a pressure force of 0.4 MPa.

[0048] When the capacity of the pressure chamber 109 is changed by the drive of the piezoelectric element 107 as described above, the pressure is temporarily changed in the pressure chamber 109, with the result that a pressure differential is generated by the pressure at the bilateral ends of the first flow pass and the second flow pass connected to the pressure chamber. Then, the fluid is transported in a direction which eliminates this differential pressure. Accordingly, when the piezoelectric element 107 oscillates at the same

magnitude, a large differential pressure can be created in the first flow pass and the second flow pass depending on the degree of the rapidity of the oscillation (increasing deformation per unit time).

[0049] FIG. 3 shows the relationship between differential pressure and the flow pass resistance of the first flow pass and the second flow pass of the micro pump of the present embodiment. FIG. 3(A) shows the first flow pass, and FIG. 3(B) shows the second flow pass. The flow pass resistance corresponds to the pressure loss coefficient when a fluid flows through the flow pass; when the fluid volume flowing per unit time is designated flow Q, and the pressure loss caused by the fluid flowing through the flow pass is designated ΔP, the flow pass resistance R [$N \cdot s/m^5$] is determined by $R=\Delta P/Q$. Furthermore, N is the force (Newtons), and s is time (seconds). The values shown in FIG. 3 are values measured by determining the pressure dependence of the flow pass resistance from the flow speed when a fluid flows through the first flow pass and the second flow pass at a specific pressure.

[0050] Referring to FIG. 3, it can be understood that the second flow pass 117 has a small flow pass resistance pressure dependence, and the first flow pass 115 has a larger flow pass resistance pressure dependence. The

following properties are derived from this difference in flow pass resistance pressure dependence. That is, when the differential pressure is large, i.e., when the absolute value of the rate of change of the volume of the pressure chamber per unit time is large, fluid flows with more difficulty in the first flow pass compare to the second flow pass, and when the differential pressure is small, i.e., when the absolute value of the rate of change of the volume of the pressure chamber 109 is small, a fluid flows more freely through the first flow pass compared to the second flow pass. Accordingly, when the absolute value of the rate of change of the volume of the pressure chamber 109 is large, the fluid subject to the volume change of the pressure chamber 109 mainly flows through the second flow pass 117, and when the volume rate of change of the pressure chamber 109 is small, the fluid subject to the volume change of the pressure chamber 109 mainly flows through the first flow pass 115.

[0051] The waveform of the voltage applied to the piezoelectric element 107 is described below. The voltage applied to the piezoelectric element 107 is generated by the drive unit 120. In the micro pump 100 of the present embodiment, it is necessary to generate a difference in the absolute value of the pressures when

pressurizing and depressurizing the pressure chamber 109. FIG. 4 shows the deportment of a fluid and a first voltage waveform applied to a piezoelectric element. FIG. 4(A) shows a first voltage waveform applied to the piezoelectric element 107. When the voltage applied to the piezoelectric element 107 is increased, the piezoelectric element 107 and the oscillation plate 105 are subject to warping deformation on the pressure chamber 109 side, which results in decreasing the volume of the pressure chamber 109. Conversely, when the voltage applied to the piezoelectric element 107 is reduced, the volume of the pressure chamber 109 is increased due to the lesser amount of displacement of the warping deformation of the piezoelectric element. Referring to FIG. 4(A), the waveform of the voltage applied to the piezoelectric element 107 is such that the rise time t1 is longer than the fall time t2. Accordingly, when a voltage having the waveform shown in FIG. 4(A) is applied to the piezoelectric element 107, the absolute value of the rate of volume change per unit time of the pressure chamber 109 is smaller at time t1 than at time t2. Therefore, the first flow pass 115 allows easier fluid flow at time t1 than at time t2, and the second flow pass 117 has virtually unchanged fluid flow at time t1 and time t2.

[0052] FIG. 4(B) shows the deportment of a fluid when a voltage having the waveform shown in FIG. 4(A) is applied to the piezoelectric element 107. Time is plotted on the horizontal axis, and fluid location is plotted on the vertical axis. The fluid location is shown with the positive direction on the right side in FIG. 1. Referring to FIG. 4(B), for the previously described reasons, the macro fluid flow is in the positive direction, i.e., flows in a direction from the left side toward the right side in FIG. 1.

[0053] FIG. 5 shows the deportment of a fluid and a second voltage waveform applied to the piezoelectric element 107. FIG. 5(A) shows a second voltage waveform applied to the piezoelectric element 107. Referring to FIG. 5(A), the voltage waveform applied to the piezoelectric element 107 has a rise time t1 that is shorter than the fall time t2. Accordingly, when a voltage having the waveform shown in FIG. 5(A) is applied to the piezoelectric element 107, the absolute value of the volume change rate per unit time of the pressure chamber 109 is greater at time t1 than at time t2. Therefore, the first flow pass 115 allows easier fluid flow at time t1 than at time t2, and the second flow pass 117 has virtually unchanged fluid flow at time t1 and time t2.

[0054] FIG. 5(B) shows the deportment of a fluid when a voltage having the waveform shown in FIG. 5(A) is applied to the piezoelectric element 107. Time is plotted on the horizontal axis, and fluid location is plotted on the vertical axis. The fluid location is shown with the positive direction on the right side in FIG. 1. Referring to FIG. 5(B), for the previously described reasons, the macro fluid flow is in the negative direction, i.e., flows in a direction from the right side toward the left side in FIG. 1.

[0055] The macro flow of the fluid can be expressed by the fluid transport efficiency. The fluid transport efficiency is determined by the ratio of the first flow pass 115 flow pass resistance to the second flow pass 117 flow pass resistance at a high differential pressure, and the ratio of the first flow pass 115 flow pass resistance to the second flow pass 117 flow pass resistance at low differential pressure. When the ratio of the first flow pass 115 flow pass resistance relative to the second flow pass 117 flow pass resistance at low differential pressure is designated Kl, and the ratio of the first flow pass 115 flow pass resistance relative to the second flow pass 117 flow pass resistance at high differential pressure is designated Kh, the fluid transport efficiency α can be expressed by equation (1) below.

[0056] $\alpha=(1/(1+Kl))-(1/(1+Kh))$ (1)

[0057] In the micro pump 100 of the present embodiment, the differential pressure at low pressure is 10 kPa, and the differential pressure at high pressure is 100 kPa. At this time, the flow pass resistance ratio at low pressure is Kl is nearly equal to 0.56, and the flow pass resistance Kh at high pressure is nearly equal to 1.17. When these values are substituted in eq. (1), the fluid transport efficiency α is approximately 18% in both the positive direction and the negative direction.

[0058] It can be understood from eq. (1) that in order to improve the fluid transport efficiency α it is desirable that Kl is made as small as possible, and Kh is made as large as possible. For this reason one flow pass has a variable flow pass resistance via differential pressure which is as small as possible (laminar deportment), and the other flow pass has a variable flow pass resistance via differential pressure which is as large as possible (turbulent deportment). It is further desirable that the values of the flow pass resistance of the first flow pass and the second flow pass at low pressure and high pressure are reversed.

[0059] The region of changing differential pressure is desirably shifted entirely to the high pressure direction to improve fluid transport efficiency. Specifically, a

pressure of 10 kPa at low pressure and a pressure of 100 kPa at high pressure is more advantageous than having a pressure of 1 kPa at low pressure and a pressure of 10 kPa at high pressure.

(Drive Voltage Modifications)

[0060] Since the Most typically the waveforms shown in FIGS. 4(A) and 5(A) are used to differentiate the time required to raise the voltage applied to the piezoelectric element 107 and the time required for voltage fall. The waveform is not limited to these examples insofar as the waveform is not symmetrical for rise and fall on the time axis.

[0061] FIG. 6 shows a modification of the waveform of a voltage applied to a piezoelectric element 107 by the drive unit 120 of the micro pump of the present embodiment. Referring to FIG. 6, FIG. 6(A) shows a waveform when fluid is transported in the positive direction, and FIG. 6(B) shows a waveform when a fluid is transported in the negative direction. In this example, a time t3 during which the voltage does not change is included between the time t1 and the time t2.

[0062] When the fluid is transported in the positive direction, the time t1 is longer than the time t2, and when the fluid is transported din the negative direction,

the time t1 is shorter than the time t2. Other than the addition of a time t3 during which the voltage does not change inserted between the time t1 and the time t2, the waveforms are identical to those shown in FIGS. 4(A) and 5(A). Sine the voltage does not change in time t3, the volume of the pressure chamber 109 does not change, and the differential pressure of the first flow pass 115 and the second flow pass 117 is zero. The fluid can be transported in a positive direction and negative direction by applying a voltage of the waveform shown in FIG. 6(A) to the piezoelectric element 107.

[0063] The reason for providing the time t3 is to mitigate the influence of oscillation of the piezoelectric element due to inertia after voltage application. That is, directly after the voltage value peaks, the force acting on the piezoelectric element increases so as to cause deformation due to inertia, and a force acts to restore the element to the original state by a restorative force due to elasticity, such that unnecessary oscillation is generated. While this oscillation remains there is a possibility that a desired deformation will not be obtained due to the influence of the oscillation when the voltage falls. In this case, a time t3 is provided during which the voltage does not change after the voltage value peaks, so as to await the

reduction of this unnecessary oscillation and suppress its influence to a minimum level.

[0064] The shapes of the first flow pass 115 and the second flow pass 117 are described below. The second flow pass 117 requires a shape which generates a flow attaining the boundary layer of laminar flow. For this reason it is desirable that the Reynolds number Re is low, and the ratio of the flow pass length to the flow pass width is large. The Reynolds number Re is a generally index value used in fluid dynamics. The As the Reynolds number increases it represents a value approaching the turbulent flow range. The Reynolds number can be expressed as $Re=\rho vd/\eta$ when the fluid density is designated ρ, the fluid coefficient of viscosity is designated η, flow speed is designated v, and the length of one edge when the flow pass has a rectangular cross sectional configurations taken in a plane that is orthogonal to the flow direction is designated d.

[0065] Although the Reynolds number differs depending on the cross sectional configurations taken in a plane that is orthogonal to the flow direction, the theory of an annular flow pass is well known. That is, in an annulus of diameter d and length L, it is desirable that $L>k\times Re\times d$ in laminar flow ($Re<2320$). The constant k is

k=0.065 as determined by Nikuradse's test, and k=0.058 as determined by Langharr's test.

[0066] Basically, a flow pass having a long length and a uniform cross sectional configurations taken in a plane that is orthogonal to the flow direction is desirable, but the shape is not limited to this shape insofar as the shape produces a flow which attains the boundary layer. Even when there is insufficient boundary layer attainment, it is desirable that the laminar flow have a high degree of boundary layer attainment compared to the first flow pass 115.

[0067] On the other hand, the first flow pass 115 requires a shape producing turbulent flow or vortex, or a shape including a range if insufficient formation of the boundary layer. The first flow pass 115 has a shape which increases the value of the flow pass resistance as the differential pressure increases, and an example of such a shape is shown below. The differential pressure is the difference in pressure at bilateral ends of the flow pass.

[0068] Parameters of the shape of the first flow pass 115 are described below.

[0069] (1) High Reynolds number Re

Although the optimum value depends on shape, an annular shape requires Re>2320 at least at peak flow speed (turbulent flow).

[0070] (2) Shapes having a relatively small flow pass length L relative to flow pass diameter d

Although suitable values differ depending on shape, an annular shape requires $L<0.065\times Re\times d$ at least at peak flow speed.

[0071] FIG. 7 shows a first example of the shape of the flow pass 115. Referring to FIG. 7, when the first flow pass 115 has a square cross sectional configurations taken in a plane that is orthogonal to the flow direction, the length of one edge is designated d, and the length of the first flow pass 115 is designated L, the condition is that ratio L/d is relatively small. When the first flow pass 115 has a circular cross sectional configurations taken in a plane that is orthogonal to the flow direction, the diameter is designated d, and the flow pass length is designated L, the condition is that the flow pass length and the ratio L/D are small. In particular, the condition is that $L/d<0.065\times Re$ at peak flow speed.

[0072] FIG. 8 shows a second example of the shape of the first flow pass. Referring to FIG. 8, the first flow pass 115A has a shape wherein the width gradually becomes larger from the pressure chamber 109 to ward the first

fluid chamber 111. In this instance, also, the shape of the first flow pass 115A satisfies condition (2).

[0073] FIG. 9 shows a third example of the shape of the first flow pass. Referring to FIG. 9, the first flow pass 115B has a shape wherein the cross sectional area taken in a plane that is orthogonal to the flow direction changes in two stages, and the change in area is abrupt. The cross sectional configurations taken in a plane that is orthogonal to the flow direction of the first flow pass 115B may be circular or rectangular. Even examples other than those of FIGS. 8 and 9 may be suitable by satisfying the conditions by a shape which changes the cross section perpendicular to the direction of fluid flow from one end to the other end of the first flow pass.

[0074] FIG. 10 shows a fourth example of the shape of the first flow pass. The first flow pass 115C is disposed between the pressure chamber 109 and the first fluid chamber 111, and the fluid flow direction is not a straight line but rather is bent.

[0075] FIG. 11 shows a fifth example of the shape of the first flow pass. The first flow pass 115D is provided with an obstruction 131 in the approximate center. The cross section shape of the obstruction 131 perpendicular to the fluid flow direction becomes smaller

from the pressure chamber 109 toward the first fluid chamber 111.

[0076] FIG. 12 shows a sixth example of the shape of the first flow pass. Referring to FIG. 12 an obstruction 131A is disposed near the first flow pass 115E of the pressure chamber 109.

[0077] FIG. 13 shows a seventh example of the shape of the first flow pass. Referring to FIG. 13, the first flow pass 115F has the same width as the pressure chamber 109 and the first fluid chamber 111, and connects the pressure chamber 109 and the first fluid chamber 111. An obstruction 131B is provided in the first flow pass 115F between the pressure chamber 109 and the first fluid chamber 111. The obstruction 131B has a cross section which becomes smaller from the pressure chamber 109 toward the first fluid chamber 111. Since an obstruction 131B is provided in the first flow pass 115F, the area through which a fluid can pass in the first flow pass 115 is smaller than the cross sectional area of the pressure chamber 109 and the cross sectional area of the first fluid chamber 111.

(First Modification of the Micro Pump)

[0078] A modification of the micro pump is described below. The modified micro pump provides directionality

in the first flow pass 115. Directionality is the difference in the flow resistance when fluid flows from the pressure chamber 109 to the first fluid chamber 111 and the flow resistance when the fluid flows from the first fluid chamber 111 to the pressure chamber 109 under condition of the same absolute value of differential pressure. In this way by providing directionality in the first flow pass 115, fluid can be transported in a single direction even when a sine wave voltage is applied to the piezoelectric element 107 by the drive unit 120. Generally, when a fluid is transported unidirectional, it is most effective to apply a sine wave voltage to the piezoelectric element 107 so as to vibrate the oscillation plate 105 at the resonance point. Accordingly, fluid can be transported in a direction in accordance with the directionality of the first flow pass 115 by providing directionality in the first flow pass 115 and applying a sine voltage to the piezoelectric element 107. In this instance, a fluid can be efficiently transported since a sine wave voltage is applied to the piezoelectric element 107 to vibrate the oscillation plate 105 at the resonance point.

[0079] On the other hand, a fluid can be transported in a direction opposite the direction in accordance with the directionality of the first flow pass 115 by applying

voltages having different time required for voltage rise and time required for voltage fall to the piezoelectric element 107 for the same reason as described in the embodiment of FIG. 2. In this way a micro pump is provided wherein fluid transport is achieved efficiently in a direction in accordance with the directionality of the first flow pass 115, and fluid transport is achieved in a direction opposite the direction in accordance with the directionality of the first flow pass 115.

[0080] FIG. 14 is a plan view of a first modification of the micro pump of the present embodiment. Referring to FIG. 14, the micro pump 100 of the first modification is provided with a first flow pass 130 wherein the width increases from the pressure chamber 109 toward the first fluid chamber 111. For this reason the flow resistance when fluid flows from the pressure chamber 109 to the first fluid chamber 111 is smaller than the flow resistance when fluid flows from the first fluid chamber 11 to the pressure chamber 109. As a result, when the time of pressurization and the time of depressurization of the pressure chamber 109 are identical, there is a macro fluid flow from the second fluid chamber 113 through the pressure chamber 109 to the first fluid chamber 111.

[0081] Furthermore, if the time of pressurization of the pressure chamber 109 is less than the time of depressurization, macro fluid flow is from the first fluid chamber 111 through the pressure chamber 109 to the second fluid chamber 113 in the same way as the embodiment shown in FIG. 2.

[0082] FIG. 15 shows an example of voltage applied to the piezoelectric element 107 by the drive unit 120 of the first modification of the micro pump 100 of the present embodiment. FIG. 15(A) shows the waveform when fluid is transported from the pressure chamber 109 to the first fluid chamber 111, and FIG. 15(B) shows the waveform when the fluid is transported from the first fluid chamber 111 to the pressure chamber 109. The waveform shown in FIG. 15(A) is a sine wave. This sine wave is the waveform of the voltage applied to the piezoelectric element 107 to vibrate the oscillation plate 105 at the resonance point. As a result, when this sine wave voltage is applied to the piezoelectric element 107, there is a macro fluid flow in the direction in accordance with the directionality of the first flow pass 130, i.e., fluid flows from the first fluid chamber 11 toward the pressure chamber 109.

[0083] The waveform shown in FIG. 15(B) shows that the time t1 of voltage increase is shorter than the time t2

of voltage decrease. For this reason the time of decreasing volume of the pressure chamber 109 is shorter than the time of increasing volume. As a result, the differential pressure of the first flow pass 130 when the volume of the pressure chamber 109 is decreasing is greater than the differential pressure of the first flow pass 130 when the volume of the pressure chamber 109 is increasing. This results in the fluid flowing more readily in the first flow pass 130 in time t2 than in time t1, whereas the ease of flow is virtually unchanged in time t1 or time t2 in the second flow pass 117. Accordingly, when a voltage of this waveform is applied to the piezoelectric element 107, macro fluid flow is in a direction opposite the direction of directionality of the first flow pass 130, i.e., fluid flows from the first fluid chamber 11 toward the pressure chamber 109.

[0084] FIG. 16 shows another example of the waveform of the voltage applied to the piezoelectric element 107 by the drive unit 120 in the first modification of the micro pump 100 of the present embodiment. FIG. 16(A) shows the waveform when fluid is transported from the pressure chamber 109 toward the first fluid chamber 111, and FIG. 16(B) shows the waveform when the fluid is transported from the first fluid chamber 111 toward the pressure chamber 109. Referring to FIG. 16(A), the

waveform of the voltage is rectangular. The time of increasing volume of the pressure chamber 109 and the time of decreasing volume are identical. In the first flow pass 130, the absolute value of the differential pressures of the flow pass 130 are identical when increasing and decreasing the volume of the pressure chamber 109. Therefore, fluid flows in the direction in accordance with the directionality of the first flow pass 130, i.e., fluid flows from the pressure chamber 109 toward the first fluid chamber 111.

[0085] Referring to FIG. 16(B), the time t1 of increasing voltage is shorter than the time t2 of decreasing voltage. Furthermore, a time t3 wherein the voltage does not change is included between the time t1 and the time t2. Since the time t1 of increasing voltage is shorter than the time t2 of decreasing voltage, the time t1 of decreasing volume of the pressure chamber 109 is shorter than the time t2 of increasing volume. As a result, the absolute value of the differential pressure of the first flow pass at time t1 is greater than the absolute value of the differential pressure of the first flow pass 130 at time t2. Therefore, fluid flows in the direction opposite the directionality of the first flow pass 130, i.e., fluid flows from the pressure chamber 109 toward the second fluid chamber 113.

(Second Modification of the Micro Pump)

[0086] FIG. 17 is a plan view of a second modification of the micro pump 100of the present embodiment. If the first flow pass and the second flow pass are compared relatively and the difference in rate of change of the flow pass resistance relative to differential pressure is recognized, the second flow pass also may be provided directionality in addition to the first flow pass without problem. The condition is that the rate of change of the flow pass resistance relative to differential pressure in the first flow pass is greater than the rate of change of the flow pass resistance in the second flow pass. The efficiency of transporting fluid when a sine wave voltage is applied to the piezoelectric element 107 can be improved by providing both the first flow pass and the second flow pass with identical directionalities.

[0087] Referring to FIG. 17, the second flow pass 131 has a shape wherein the width increases from the second fluid chamber 113 toward the pressure chamber 109. Therefore, the flow pass resistance when fluid flows from the second fluid chamber 113 toward the pressure chamber 109 is less than the flow pass resistance when the fluid flows from the pressure chamber 109 toward the second fluid chamber 113. If the time of decreasing volume and

the time of increasing volume of the pressure chamber 109 are identical, the macro fluid flow is in a direction in accordance with the directionality of the first flow pass 130 and the second flow pass 131, i.e., the fluid flows from the second fluid chamber 113 toward the pressure chamber 109.

[0088] On the other hand, if the time of decreasing volume of the pressure chamber 109 is shorter than the time of increasing volume, the macro fluid flow is in a direction opposite the directionality of the first flow pass 130 and the second flow pass 131, i.e., fluid flows from the first fluid chamber 111 toward the pressure chamber 109.

[0089] FIG. 18 shows the relationship between the differential pressure and the flow pass resistance of the first flow pass 130 and the second flow pass 131 of the second modification of the micro pump 100 of the present embodiment. FIG. 18(A) shows the case of the first flow pass 130, and FIG. 18(B) shows the case of the second flow pass 131. Referring to FIG. 18, the flow pass resistance when the differential pressure is positive for both the first flow pass and the second flow pass is less than the flow pass resistance when the differential pressure is negative. Accordingly, the first flow pass and the second flow pass have directionality.

Furthermore, the percentage change in the flow pass resistance relative to the change in differential pressure of the first flow pass is greater than the percentage change in the flow pass resistance relative to the differential pressure of the second flow pass. Therefore, fluid can flow can be transported in a direction opposite to the fluid flow direction when the time of increase and the time of decrease are identical by having the time of decreasing volume of the pressure chamber shorter than the time of increasing volume.

[0090] The micro pump of the embodiment described above generates turbulent flow only in the first flow pass 115 and flow pass 130 when fluid flow is steep. Therefore, the direction of macro fluid flow is controlled by switching between voltages of two waveforms to drive the piezoelectric element 107, so as to transport the fluid in a standard direction and an opposite direction.

[0091] A stable drive micro pump is realized which has improved responsiveness and durability compared to method which operate a check valve. In addition, the structure of the micro pump is simple, and the micro pump itself is compact.

[0092] Fluid is transported with high precision and without pulsation since only a small amount of fluid is

transported per single pulse signal of the voltage driving the piezoelectric element 107.

[0093] The micro pump 100 of the embodiments uses the unimorph oscillation of the adhered piezoelectric element 107 and the oscillation plate 105 functioning as an actuator, but the present invention is not limited to unimorph oscillation insofar as the increase and decrease in volume of the pressure chamber 109 can be repeated. For example, a diaphragm may be oscillated using horizontal oscillation or vertical oscillation of a piezoelectric element, shearing deformation of the piezoelectric element may be used, or a micro tube using piezoelectric material may be reduced in the diameter direction. Shearing deformation of the piezoelectric element is also referred to as shear mode deformation, and is a deformation cause by shearing and element obliquely when the bifurcation direction of the piezoelectric element intersects the electric field direction. Alternatives to a piezoelectric element include methods which deform a diaphragm using electrostatic force, and methods using shape-memory alloy on part of the oscillation element.

[0094] Although the present invention has been fully described by way of examples with reference to the accompanying drawings, it is to be noted that various

changes and modification will be apparent to those skilled in the art. Therefore, unless otherwise such changes and modifications depart from the scope of the present invention, they should be construed as being included therein.